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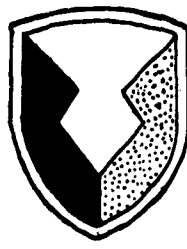
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COATING and CHEMICAL LABORATORY



CCL REPORT NO. 146

DEVELOPMENT AND EVALUATION OF A LABORATORY BENCH
SCALE HEAT TRANSFER APPARATUS

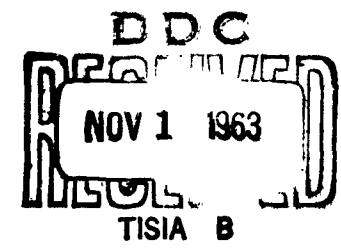
BY

LT. ROBERT R. BUNTIN

AMCMS CODE NO. 5025.11.803
DA PROJECT 1-A-0-24401-A-109

30 AUGUST 1963

ABERDEEN PROVING GROUND
MARYLAND



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U.S. Army Coating and Chemical Laboratory
Aberdeen Proving Ground
Maryland

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ABSTRACT

↙ This report describes work done on the development and evaluation of a laboratory bench scale heat transfer apparatus for determining the heat transfer efficiency of automotive coolants.

A bench unit was constructed and used for measuring forced convection heat transfer coefficients of several typical coolants. Measurements were made under boiling and non-boiling conditions. The method employed uses a small electrically heated wire as a heat dissipating surface and at the same time as a resistance thermometer for determining surface temperature.

The usefulness of the unit has been demonstrated by preliminary data showing significant differences in heat transfer ability of presently used coolants, especially at higher metal temperatures. The unit is also capable of providing data on the effect of corrosion or other surface reaction on heat transfer. ↗

1. INTRODUCTION

Aberdeen Proving Ground, Maryland, was directed by AMC under AMCMS Code 5025.11.803, reference program directive dated 15 October 1962, to conduct research and development on automotive coolants to obtain improved coolants. In order to carry out research in this area it was deemed necessary to develop a method whereby the heat transfer ability of new and experimental coolants can be evaluated.

The purpose of an engine coolant is to accept waste heat from the combustion zone of the engine and carry this heat to the radiator where it is transferred to the atmosphere. Other factors such as low corrosivity, heat stability, ease of handling, low cost, etc. are also important.

The ability of a fluid to transfer heat to or from a surface is most conveniently characterized by the heat transfer coefficient "h". This parameter is defined by

$$h = \frac{Q}{A (T_S - T_B)} \quad (1)$$

where h = heat transfer coefficient, cal/sec cm² °C.
 Q = rate of heat transfer, cal/sec
 A = surface area of transfer, cm²
 T_S = surface temperature, °C.
 T_B = bulk fluid temperature, °C.

For the type of heat transfer known as forced convection, "h" for any fluid is primarily a function of the density, heat capacity, thermal conductivity, viscosity of the fluid, the nature of the surface and the fluid flow rate past the surface. There are many correlations relating these properties to "h" for various flow conditions and if the values of these properties are known, "h" can be calculated rather easily for simple flow situations. Such a calculation was carried out for the case of water flowing in an automobile radiator in "Report on 15 Day Tour of Duty" by H. Col. Hugh D. Sims (see reference 3). The following equation applies:

$$h = \frac{0.023 V^{0.8} \rho^{0.8} C_p^{0.3} k^{0.7}}{D_e^{0.2} \mu^{0.5}} \quad (2)$$

where h = heat transfer coefficient, cal/sec cm² °C
 V = velocity of flow, cm/sec
 ρ = fluid density, gm/cm³
 C_p = fluid heat capacity, cal/gm °C
 k = fluid thermal conductivity, cal/sec cm °C
 D_e = equivalent diameter of flow channel, cm
 μ = fluid viscosity, gm/cm sec.

Substitution of appropriate values for water into this equation allows calculation of "h". Calculations for fluids other than water and for mixtures, eg. glycol and water can also be carried out using the proper values of ρ , C_p , k , and μ . Thus, one approach to the problem of evaluating heat transfer

efficiency of an engine coolant would be to obtain values for the important fluid properties and calculate the value of "h" using an equation such as equation (2). However, since data on Cp and k are limited (see reference 3), it would be necessary to determine these values experimentally for new and experimental coolants.

While the flow situation in a radiator is rather simple, the nature of heat transfer in the engine block coolant passages is more complex. This is due to the highly irregular flow path and also to the existence of very hot zones near the tops of the cylinder and valve ports where local boiling can take place. The fact that boiling does take place in the engine block means that other factors such as boiling point, latent heat of vaporization, vapor density, and surface tension are important factors in formulating engine coolants. Since heat transfer efficiency at "hot spots" is vital to engine performance and life, considerable attention must be devoted to this aspect of the coolant problem. For this complex situation no correlation is available for satisfactorily predicting the heat transfer efficiency of a new coolant. It is therefore necessary to develop a means of experimentally measuring the ability of fluids to transfer heat not only in the purely convective situation found in an automobile radiator and cooler parts of the engine block, but also in the boiling situation which prevails in hotter zones of the block.

The heat transfer literature contains many techniques for measuring heat transfer coefficients of flowing fluids in both boiling and non-boiling convection situations. See reference 6. However, tests for the specific purpose of determining the heat transfer efficiency of engine coolants are not so numerous. Perhaps the best test for this purpose is that described in reference 7. An actual engine is instrumented so that temperatures at various points of the block and flow system can be measured. The heat transfer efficiency of a fluid can then be evaluated directly by observing the temperatures produced during operation of the engine. The best coolant gives lowest metal temperatures in critical hot zones and greatest temperature drop on passing through the radiator. The equipment required for such a set-up, however, is quite expensive and a less complex unit is desired for screening and exploratory work on new coolants. This report describes the work done on development of such a test.

II. DETAILS OF TEST

A. General Principles

The requirements for any forced convection heat transfer test are:

1. A heat transfer surface of known area must be placed in contact with the flowing test fluid.
2. Heat must be dissipated through the surface to the fluid at a known rate.
3. The temperature of the surface must be determined.
4. The bulk temperature of the fluid must be determined.

In our case it must also be possible to produce surface temperatures sufficiently high to cause small bubble boiling on the heating surface. In this manner the heat transfer coefficient for boiling can be obtained as well as that for simple convection. In either case the desired heat transfer coefficient is calculated from

$$h = \frac{Q}{A (T_S - T_B)}$$

The technique described here for determining values of "h" makes use of a small wire which acts as the heating surface and at the same time as a resistance thermometer. The wire is mounted in a test cell through which the fluid under test is circulated. By passing electric current through the wire heat is generated which causes the temperature of the wire to rise until the rate of heat loss to the flowing fluid equals the rate of generation. At this steady state condition the current (I) through the wire and the voltage (V) across the wire are measured. The heat dissipation rate (power) is then calculated from the relation

$$Q = 0.23889 EI \quad (3)$$

where Q = heat dissipation rate, cal/sec
 E = voltage across cell wire, volts
 I = current through cell wire, amps
 (the factor 0.23889 converts from watts to cal/sec)

The resistance of the wire is calculated by

$$R = E/I \quad (4)$$

where R = resistance of the cell wire, ohms.

From a calibration curve or equation relating resistance to temperature of the wire the temperature T_S is obtained. The temperature T_B of the bulk stream is obtained from a thermometer at the cell inlet with a correction applied for temperature increase in the cell. The heat transfer coefficient "h" can then be calculated. Values of "h" are obtained over a range of surface temperatures. A plot of "h" vs. surface temperature then serves to characterize the heat transfer ability of the test fluid. This plot can be compared to a similar plot for a different fluid, such as distilled water, and conclusions reached as to which is the better coolant from the standpoint of heat transfer.

By using different metals for the heating wire information may be obtained about the effect of a specific metal surface on the heat transfer coefficient. No significant difference would be expected between results obtained on clean surfaces of platinum and steel, for example, using water as the coolant fluid. However, after corrosion of the steel has taken place a considerable difference due to a scale buildup might be expected. Such an effect would not be due to any change in the heat transfer ability of the water itself but to the change in surface of the metal due to the corrosive properties of the fluid. Such additional information on the interdependence of corrosion (or other surface altering action) and heat transfer should be considered in evaluating heat transfer properties of the coolant. It should

be kept in mind however, that this test is limited to the use of metals and alloys which can be obtained in the form of small wires. Inferences concerning the behavior of larger scale structural materials based on test results using pure metals or simple alloys should be made with caution.

B. Test Equipment

For the purpose of discussion the test equipment may be divided into two distinct, functional parts. One is the flow system through which the test fluid is circulated. The other is the electrical circuit for generating heat in the test wire and measuring the effects produced.

Figure 1 in the appendix is a schematic diagram of the fluid flow circuit. The fluid reservoir is a 1000 ml. flask heated by a suitable heating mantle operating on voltage supplied by a variable transformer. The heating mantle is used to maintain the fluid at the desired temperature. From the reservoir the fluid is circulated by a centrifugal laboratory pump through a flow measurement device, through the test cell, and back into the reservoir. The flow measurement tube is simply a glass tube drawn down so as to provide a flow restriction which will cause a measurable pressure drop between two manometer taps on either side of the restriction. A liquid-liquid manometer using CCl_4 -xylene mixture is connected to the pressure taps and the unit calibrated by observing the manometer reading at various flow rates. Flow rate is controlled by a pinch clamp located just before the test cell. Also located just before the cell is a thermometer for reading the inlet fluid temperature. This thermometer is placed as close to the cell inlet as possible with the connecting tube insulated.

A detail of the cell itself is shown in Figure 2. The large copper lead in wires pass through the center of the fitted rubber stoppers at each end of the cell tube. The small wire is centered in the tube. The object is to obtain a smooth steady flow of fluid axially along the wire.

Another important feature of the flow system is the air tight design. In most instances it is desirable to remove all air, dissolved and otherwise from the system. In order to keep air from redissolving in the fluid all air pockets must be excluded, ie. the unit must be closed and completely full of liquid. However, some provision must be made for thermal expansion of the liquid. This is achieved by using a 50 cc syringe mounted over the reservoir. Once the unit is deaerated and filled with fluid, the plunger of the syringe moves in and out with small volume changes of the system.

The electrical circuit is shown schematically in Figure 3. The part of the circuit through which the heating current flows contains an ammeter, a variable resistor, a fixed, standard resistor and the cell wire. Current is supplied by a 12 volt battery connected in parallel with a direct current rectifier. The 0 - 20 amp ammeter gives a visual reading of the current and the variable resistance, 0 - 5 ohms, provides a means of setting the current at the desired value. The standard resistor is a coil arrangement of manganin wire immersed in an oil bath. This coil has a resistance carefully measured to be 0.06362 ohms. The voltage drop across this known resistance provides the necessary information for an accurate determination

of the current. The purpose of the oil bath is to keep the coil cool at high current rates and thus prevent a change in resistance due to increased temperature. Manganin wire was used in making the coil for this same reason. Manganin has a very low temperature coefficient of resistance.

The circuit is modified slightly for low current standardization runs. A resistance of about 75 ohms and a fixed standard resistance coil having a higher resistance are inserted in the circuit. The 75 ohm resistance reduces the current to the low value required for standardization and the higher standard resistance gives a larger voltage drop for determining the small current flow.

The cell wire serves as the heat transfer surface and also as a temperature sensing element. The wires used are normally 0.004 - 0.0063 inches in diameter and approximately 3 inches in length and may be any metal which can be satisfactorily connected to the larger copper lead-in wires. A "satisfactory connection" is one in which the resistance of the junction between cell wire and copper lead is negligible compared to the resistance of the cell wire itself. Metals which can be easily soldered, eg. platinum, copper, iron, silver, etc. form satisfactory connections. Aluminum on the other hand is very difficult to connect and erratic results were obtained due to contact resistance between cell wire and lead-in.

The copper lead-in wires are AWG 10 wire. Solder connections to the cell wire are made by drilling a small hole in the end of the large wire, inserting the end of the small cell and soldering carefully using a resin core solder. Care must be taken not to kink or otherwise weaken the cell wire when assembling the cell, since a weak spot may cause the wire to burn out at high current rates.

The remainder of the electrical set up is for the measurement of voltages produced across various elements of the current carrying circuit. A high precision Rubicon potentiometer with suitable galvanometer was used to measure the necessary voltage accurately. By means of a multi-position rotary switch the potentiometer is connected across the cell wire or the 0.06362 standard resistor (or 9.91 standard resistor during low current runs). Since the cell voltage is frequently higher than the 1.6 volt range of the potentiometer several switch positions are used to introduce 1.5 volt increments of voltage from a 6 terminal BA-34 $7\frac{1}{2}$ volt dry battery into the measuring circuit so as to oppose the cell wire voltage. In this manner the potentiometer capability is extended to $7.5 + 1.6 = 9.1$ volts. If needed, additional cells can be added to extend the operating range even further.

C. Test Procedure

1. Calibration of New Wire

When a new type of wire is installed in the test cell the first step is to determine its temperature-resistance relationship. This is done by measuring the resistance of the wire at known temperatures over a range from 30°C. to 150°C. The resistance values are plotted vs. temperature and by means of a "least squares" curve fitting procedure, an equation is thus obtained relating wire resistance to temperature. The technique for obtaining

the necessary calibration data is as follows:

(1) The reservoir and flow system are filled with pure ethylene glycol or other suitable fluid with boiling point above about 160°C.

(2) Flow is started at the maximum rate and the reservoir heater is adjusted to give cell inlet temperature of about 30°C.

(3) The 75 ohm resistance and 9.91 ohm standard resistor are placed in the circuit and a low current of about 0.1 amps is passed through the cell wire. A run made using a low current is referred to throughout this report as a "standard run". During such a run the current is sufficiently small so that the heating effect in the wire is negligible. This means that the temperature of the wire is the same as the cell inlet temperature, T_1 .

(4) The voltage drops across the standard resistor and the cell wire are read. At the same time the cell inlet temperature is read.

(5) The reservoir heater is then adjusted to a temperature of about 45°C. and the same readings are again taken. This procedure is repeated increasing the temperature approximately 15°C. each time, until a temperature of 150°C. has been reached. The unit is then allowed to cool and one more set of readings is taken at a temperature of about 30°C. This last reading is a check to insure that no permanent change in the resistance of the wire has occurred.

(6) The resistance at each temperature T . is calculated using the equation:

$$R = \frac{V}{V_{ST}} \times R_{ST} \quad (5)$$

where R = resistance of the wire at the temperature of the standard run, °C
 V = voltage across the cell, volts
 V_{ST} = voltage across the standard resistor, volts
 R_{ST} = resistance of the standard resistor = 9.91 ohm.

(7) The calculated values of resistance are then fitted if possible to a straight line equation of the type

$$R = R_0 (1 + \alpha T) \quad (6)$$

where R_0 = resistance at 0°C, ohm
 α = temperature coefficient of resistance, 0°C

For data which cannot be fitted satisfactorily by a straight line, a higher order equation is used such as

$$R = R_0 (1 + \alpha T + \beta T^2) \quad (7)$$

In both cases the constants R_0 , α , and β are best obtained by the procedure of "least square fitting".

2. Measurement of Heat Transfer Coefficients

After calibration the wire is ready to be used in an initial series of measurements on distilled water. The reservoir and flow system are refilled with fresh distilled water. Flow is started at the maximum rate. (In fact almost all runs were made at the maximum flow rate of the pump.) The unit is then brought up to a temperature of about 72°C. With the syringe removed from the top of the reservoir and a vacuum line attached in its place, the flow is stopped and vacuum is applied. Vacuum is regulated so that the water in the reservoir boils vigorously, thus driving out all dissolved air. Then flow is again started and a current from the rectifier is passed through the cell wire at a rate such that the air adsorbed on the metal surface is driven off into the circulating water. During this operation air bubbles can usually be seen all along the wire. Care must be taken not to use too high a current or the wire will burn out. After the air has been driven off, slightly higher currents can be used. This deaeration process should be continued until no air bubbles remain on the wire at a current level sufficiently high to cause surface boiling. The magnitude of current required depends on the resistance of the wire and is found by preliminary trial and error. After the wire is free of air bubbles, current is stopped, and the system is again placed under vacuum to remove final traces of air from the water. The syringe and plunger are then put in place and the system is completely closed to the atmosphere. The temperature is again adjusted to about 72°C. The plunger should move freely in or out to allow for volume changes due to small temperature adjustments. The system is now ready for a series of heat transfer coefficient determinations using pure water.

At the beginning of the series a "standard run" is made at about 72°C. The readings are used later in the calculation of the resistance of the wire at 0°C.

Runs at high current rate are then made after, removing the 75 ohm and 9.91 ohm standard resistors from the circuit. The current is set by connecting the battery and rectifier in parallel and adjusting the variable 0 - 5 ohm resistance until the desired current is indicated by the ammeter. The rectifier should be set so that it supplies almost all of the current indicated by the ammeter. Voltage readings are then taken across the cell wire and the 0.06362 ohm standard resistor and the inlet temperature T_1 is recorded. Care must be taken to read average values of voltage and not be unduly influenced by random voltage fluctuation. Readings of this type are made at a number of different current settings (at intervals of 1 or 2 amps) being careful not to exceed the burn out point of the wire. Such a series will normally include several readings in the non-boiling region and several with the water boiling vigorously on the wire surface. At the end of the series another standard run at low current is made as a check to see if any change in the base resistance of the wire has taken place. The method of calculating heat transfer coefficients is as follows:

(1) The data for the two standard runs before and after the series and equation (5) are used to calculate the resistance of the wire at the temperature of the standard runs. The value of the resistance at 0°C. can then be calculated from the calibration equation for the wire. For platinum the equation is

$$R_0 = \frac{R}{1 + 0.0038T} \quad (8)$$

If the two values of R_o calculated for standard runs before and after the series are in close agreement, the average may be used in future calculations and it is assumed that R_o remained constant throughout the series. However, if there is a large difference there is strong evidence of a change in the wire due probably to corrosion. Such changes are to be expected with metals such as iron or steel. In this case it becomes necessary to repeat the series making standard runs before and after each individual high current run. The value of R_o at the time of the high current run can then be obtained by interpolation between the values of R_o calculated from the bracketing standard runs. The standard runs with high current run in between should be made as close together as possible to reduce error in the interpolation procedure. In any event the value of R_o must be known for each high current run.

(2) The resistance of the wire during each high current run is then calculated by

$$R = \frac{V}{V_{ST} \times R_{ST}} \quad (9)$$

where R = resistance of the heated cell wire, ohms
 V = voltage across the cell wire, volts
 V_{ST} = voltage across the standard resistor, volts
 R_{ST} = resistance of the standard resistor = 0.06362 ohm

(3) The temperature of the heated wire is calculated using the calibration equation. For platinum this is rearranged to

$$T_s = \frac{R - R_o}{0.0038 R_o} \quad (10)$$

where T_s = temperature of the heated wire surface, °C.

(4) The power output or heat dissipation rate of the wire is calculated using the equation

$$Q = 0.23889 E I = 0.23389 \frac{V^2}{R} \quad (11)$$

(5) The calculation of the fluid bulk temperature is made by adding a correction for temperature rise in the cell to the recorded cell inlet temperature. This correction is given by

$$\Delta T = \frac{Q}{2C_p W} \quad (12)$$

where ΔT = correction to be added to inlet temperature, °C
 Q = heat dissipation rate, cal/sec
 W = fluid flow rate, gms/sec
 C_p = fluid heat capacity, cal/gm °C

Then $T_B = T_I + \Delta T$

(6) The calculation of "h" can then be made using equation (1). However, for the purpose of the test it is more convenient to calculate the quantity "h A". That is,

$$h A = \frac{Q}{T_s - T_B}$$

This quantity is the heat transfer coefficient for the entire wire rather than for unit surface. In comparing different fluids using the same wire this quantity gives the same comparison and is easier to calculate. However, in comparing results on wires of different dimensions an adjustment must be made.

A value of $h A$ is calculated for each high current run. These values are then plotted against T_s to give a heat transfer curve such as those shown in Figure 4.

After establishing the heat transfer curve for distilled water the unit is emptied and refilled with the coolant solution of interest. The filled system is then deaerated and the series of standard runs and high current runs carried out in the same manner as in the case of water. The wire usually will not require another high current run to drive off adsorbed air unless it has been allowed to stand exposed to air for a considerable period of time. The required readings and calculations are the same as described above. A plot of the heat transfer coefficient versus surface temperature gives a curve which can then be compared to that of water.

III. TYPICAL RESULTS OF TEST

During the development of the test procedure four different types of cell wires were used for heat transfer coefficient determinations. Distilled water, ethylene glycol-water solution, and water solutions with corrosion inhibitor, Federal Specification 0-1-490 added were employed as test fluids. Typical results for each type of wire employed are discussed below:

A. Platinum

The first type of cell wire used was # 34 gauge platinum wire, which has a diameter of .0053 inches. It is easily soldered to the large copper lead in thus making very good connections. The resistance of this wire is 0.117 ohms per inch and the resistance-temperature relationship takes the form

$$R = R_0 (1 + \alpha T). \text{ with } \alpha = 0.0038$$

The value of α is taken from published data and calibration of a sample wire installed in the cell gave a value of $\alpha = 0.00376$ which agrees well with the published value. The chemical inertness of platinum makes it very suitable for this type of test.

Figure 4 shows the results of several series of runs on a 3 inch long platinum wire for four different fluids. Curve 1 represents the average of four series using pure distilled water. Curve 2 shows the effect of adding 15 grams of corrosion inhibitor, Federal Specification 0-1-490 to 1000 cc of distilled water. Curve 3 is for 50% ethylene glycol-50% water and curve 4 is for pure ethylene glycol. It is apparent that the pure water gives higher heat transfer coefficient than the glycol solution at all surface temperatures. The curve for inhibited water is fairly close to that for pure water at the

low temperature end but deviates at the upper end. The curve for pure ethylene glycol is very low showing no appreciable rise over the range of the plot. Data points for this run did show the characteristic upturn at temperatures over 200°C. The slowly rising portion of all the curves at the lower temperatures correspond to the pure convection type of heat transfer. The curves break sharply upward at higher temperatures where surface boiling takes place. The difference between the curves are due to differences in fluid properties. As mentioned previously heat transfer in the convective range is primarily dependent on density, viscosity, heat capacity and thermal conductivity. The temperatures at which the curve begins to rise are largely determined by boiling points.

These considerations do not, however, explain the difference between curves A and B. The fluid properties cited above for water are not sufficiently altered by adding inhibitor to explain the deviation of curve B especially at the high temperature end. It was noticed that a coating of the inhibitor was formed on the wire. Perhaps this coating serves to insulate the wire somewhat or interfere with bubble formation in the boiling process. In any event the plot shown in Figure 4 is typical of the type of comparisons which can be made using this test.

B. Steel

The next series of tests were made using 0.005 inch diameter steel piano wire in the cell. The resistance of this wire is 0.44 ohms per inch. The calibration data obtained for the resistance-temperature relationship was not linear but was fitted by a least squares procedure to the following equation

$$R = R_0 (1 + \alpha T + \beta T^2)$$

The two constants were found to be $\alpha = .0027454$ and $\beta = .0000024182$. The steel wires were easily soldered and because of their strength were less susceptible to being broken in assembling the cell. However, there was a definite tendency for these wires to burn out at moderate currents especially during the deaeration procedure when air bubbles were present on the wire.

The important difference between steel and platinum is the susceptibility to corrosion of the former. After a new steel wire had been installed in the cell and circulation of distilled water had begun, rusting usually began immediately. In some instances the onset of rusting was delayed for several hours but once started it proceeded rapidly until the wire was rusted through. Depending on the particular wire used this rusting was sometimes localized to a few spots while at other times was uniform over the entire length of the wire. Care must be taken in making calculations on runs of this nature to separate the change in resistance due to corrosion from the change due to increase in temperature of the heated wire. The change in resistance due to corrosion was followed by frequent standard runs at low current. The value of R_0 used in calculating heated wire temperatures was, therefore, different for each calculation.

Figure 5 shows some effects of rusting on the heat transfer coefficients. Curve A is a plot of the average values of h_A for four series with distilled water and new, uncorroded steel wires. Curve B shows the

effect of a light covering of rust. Curve C is for the same wire as Curve B but more heavily corroded. Curve D is the result of even more corrosion and Point E represents the same wire with an extremely heavy coating of scaly rust. At this point the rust was cleaned from the wire with 5 N phosphoric acid. Point F was obtained, showing a return to higher heat transfer with the cleaner wire.

No attempt was made on the plot to correct for the effect of changing wire diameter. As the wire corroded the diameter decreased thus decreasing the heat transfer area of the steel core. If a correction is made by simply basing all the data points on the same area (eg. the area of the uncorroded wire) and thus multiplying each result by $\frac{A_{\text{(new wire)}}}{A_{\text{(actual)}}}$ the effect is to shift all the points on the lower curves up somewhat, and especially Point F. Such a correction for Point F, however, places too much emphasis on the effect of area, and the true value falls somewhere between the one shown on the plot and that corrected by the area ratio.

The shape of the curves shows a change in the nature of the heat transfer. Curve A has the familiar shape for clean wire heat transfer observed with platinum wires, ie. slowly rising initial portion followed by a rapidly rising section at higher temperatures where boiling takes place. As the coating of rust builds up however, much of the resistance to heat transfer is due to the scale itself. The heat must be conducted through this layer of rather low thermal conductivity. This produces high metal temperatures although the outside surface of the scale is relatively cool and thus non boiling. The large temperature difference between metal surface and outside scale surface provides the driving force necessary to cause the heat flow through the scale layer. Looking back at Figure 4 it can be seen that the relatively small decrease in heat transfer due to addition of corrosion inhibitor to water is certainly a small price to pay if the results of rusting shown in Figure 5 can be avoided.

C. Copper

Tests on copper wires were made using .004 inch diameter wire. The resistance of this wire is 0.0507 ohms per inch. The calibration data were fitted by the equation

$$R = R_0 (1 + \alpha T) \quad \alpha = 0.004207$$

The copper wire was very satisfactory from the standpoint of ease of assembly and lack of corrosion. The low resistance of copper, however, means that a rather high current is required to achieve sufficiently high surface temperatures. Currents up to 15 amperes were used and such currents cause minor problems due to instability of the voltage source and heating up of circuit components. Satisfactory results were obtained nevertheless. Figure 6 shows the results of several series on pure water, 50% glycol-water, and inhibited water. The results are similar to those of Figure 4 on platinum wires.

During the runs on inhibited water, however, it was observed that a rather heavy coating of yellowish material gradually built up on the copper wire giving a larger decrease in hA for copper than was found in the runs on

platinum. It is possible that this was due to a true difference in the reactivity of the surface of the metals, but other factors such as the different wire diameters may also be important.

D. Aluminum

Very few successful runs were made using aluminum wires due to the problem of obtaining a good electrical contact between the cell wire and copper lead-ins. The wire used has a diameter of 0.005 inches and a resistance of 0.0521 ohms per inch. Because of the small diameter all attempts at soldering with special aluminum solders and fluxes were unsuccessful. Mechanical joints such as crimping and tight winding also failed. An attempt was made to chemically clean and copper plate the ends of the aluminum cell wire. The wire ends were cleaned in 10% NaOH saturated with NaCl then rinsed in 2% HCl. The ends were then plated for 20 minutes at a current density of 20 amps per square foot of immersed wire surface in a copper sulfate bath containing:

20 gm CuSO_4
1 cc 48% HF
100 cc distilled water

The wires prepared in this way were then soldered in the regular manner.

A few runs using such wires yielded useful data. A good calibration curve was obtained. The data fits the equation

$$R = R_o (1 + \alpha T) \text{ with } \alpha = 0.004343$$

Figure 7 shows a comparison of the results of a series using aluminum and distilled water with the distilled water runs of other metals. For this figure the values of h A have been corrected for different wire sizes in accordance with the correlation of Dr. A. C. Mueller given in reference (6). The general agreement of the curves indicates that heat transfer to pure water for different clean metal surfaces is very similar.

No other reliable data using aluminum were obtained using the method described for connecting the wire. It is believed that the technique of small wire spot welding would give better results. In this way small potentiometer leads could be welded directly onto the aluminum cell wire so that the resistance measurement would not be influenced by contact resistance.

IV. CONCLUSION AND RECOMMENDATIONS

The heat transfer test described in this report is a very satisfactory method for detecting significant differences in the heat transfer ability of coolant. It is recommended that for screening purposes the heat transfer coefficient be determined using this test method for all new and experimental coolant and inhibitor formulations. The results obtained when combined with data on corrosivity, freezing characteristics, etc. should provide a sounder basis for an overall evaluation of a new formulation.

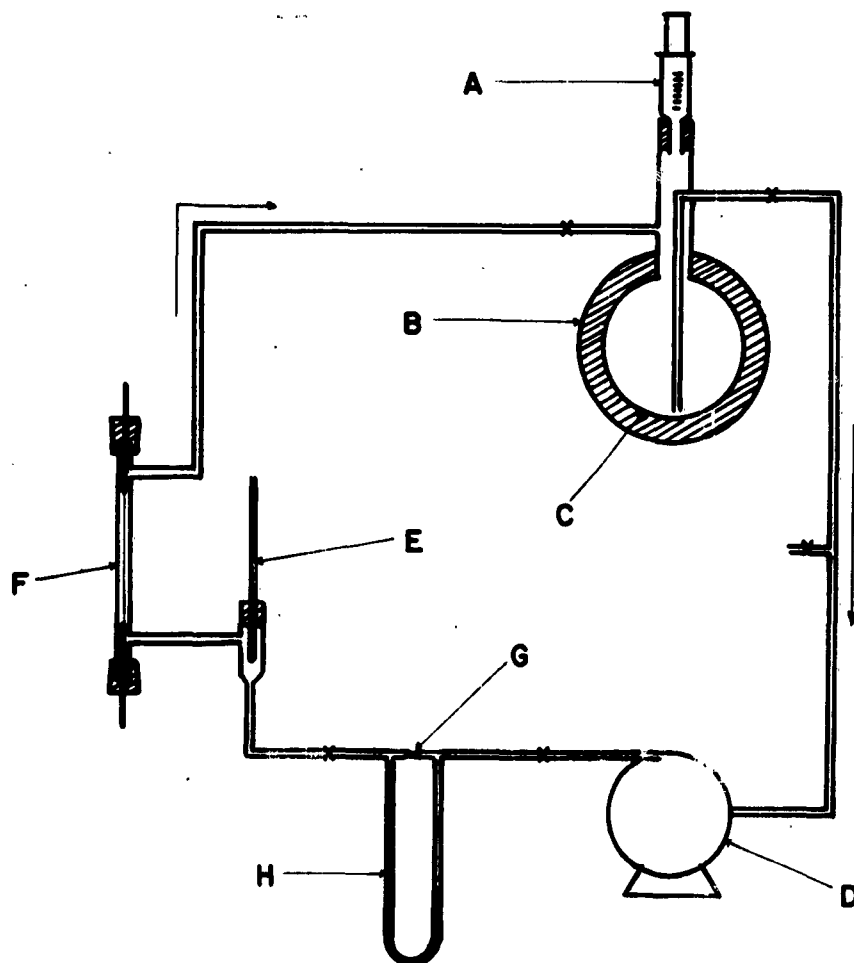
V. REFERENCES

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APPENDIX

Drawings and Graphs

**FIGURE I.
DIAGRAM OF FLOW SYSTEM**



A - 50 cc SYRINGE
B - HEATING MANTLE
C - 1000 cc FLASK
D - CENTRIFUGAL PUMP

E - THERMOMETER
F - TEST CELL
G - FLOW RESTRICTION
H - MANOMETER

FIGURE 2.
DIAGRAM OF TEST CELL
(1/2 ACTUAL SIZE)

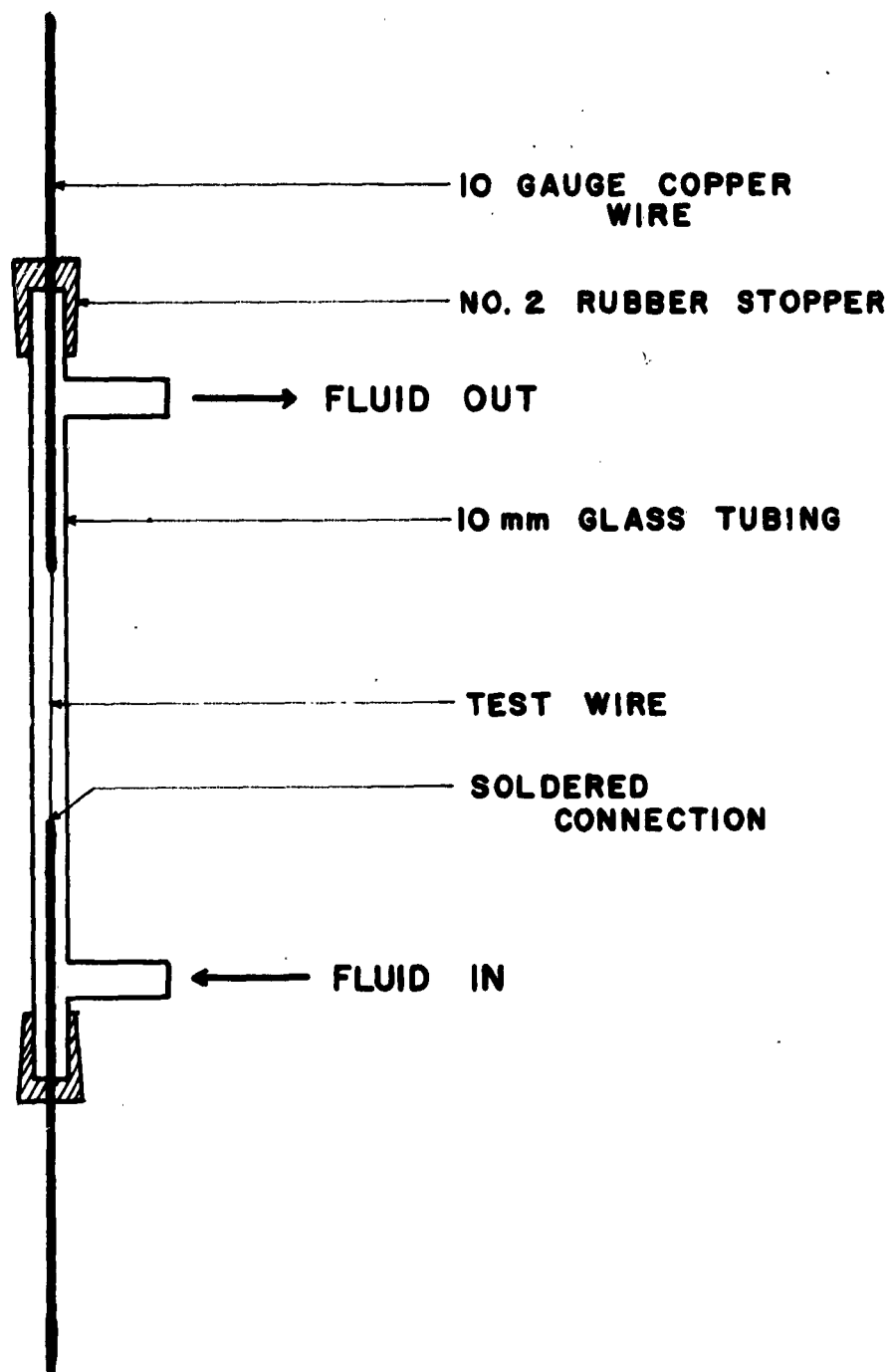
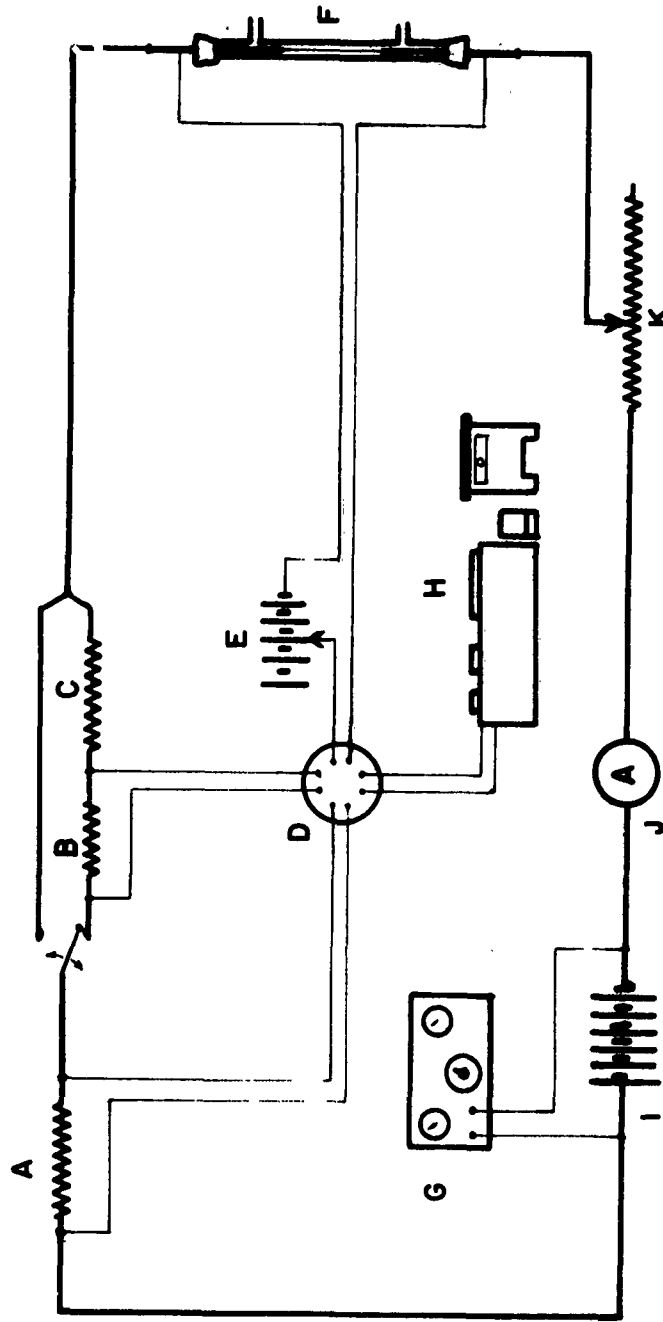
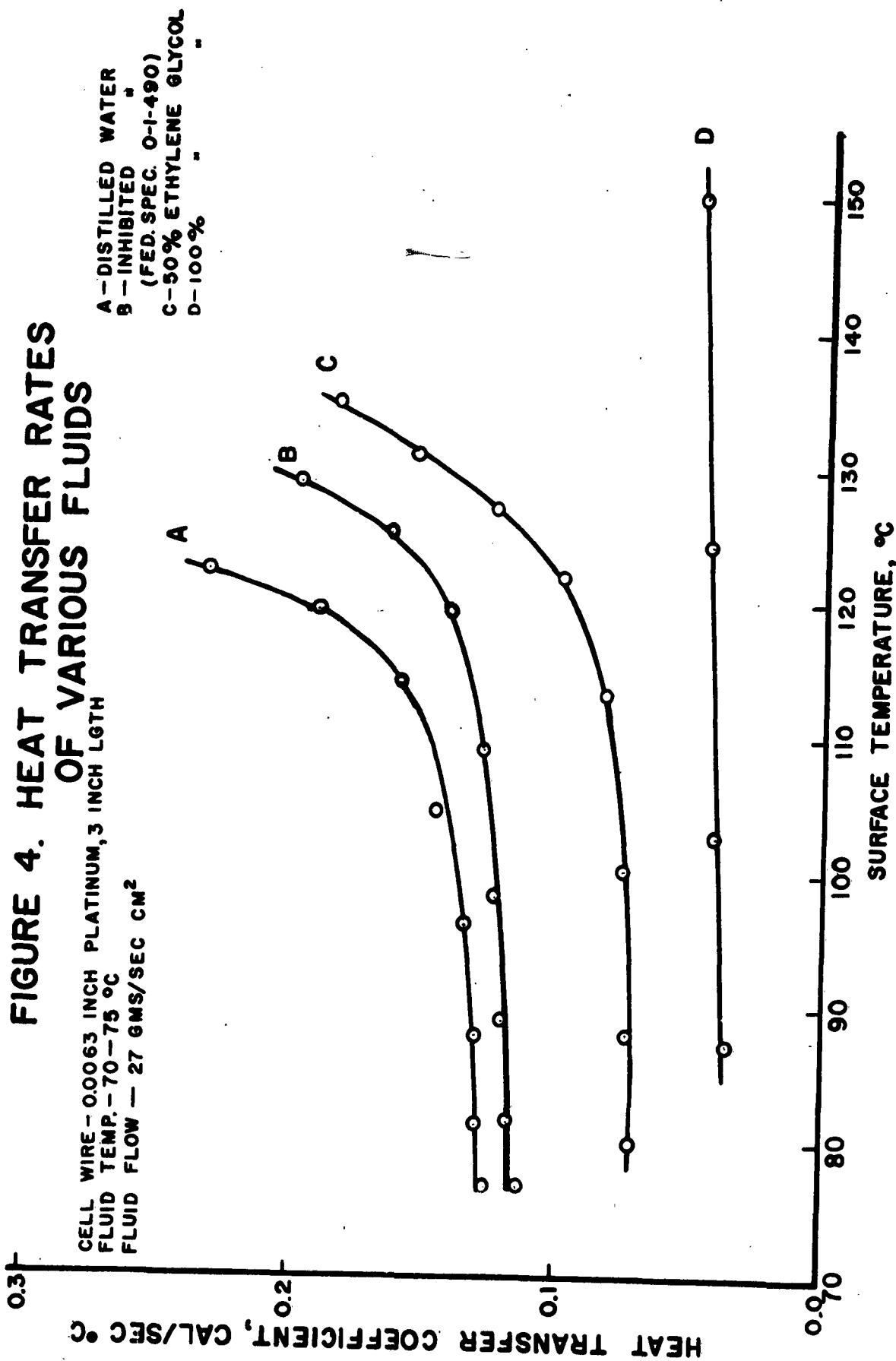


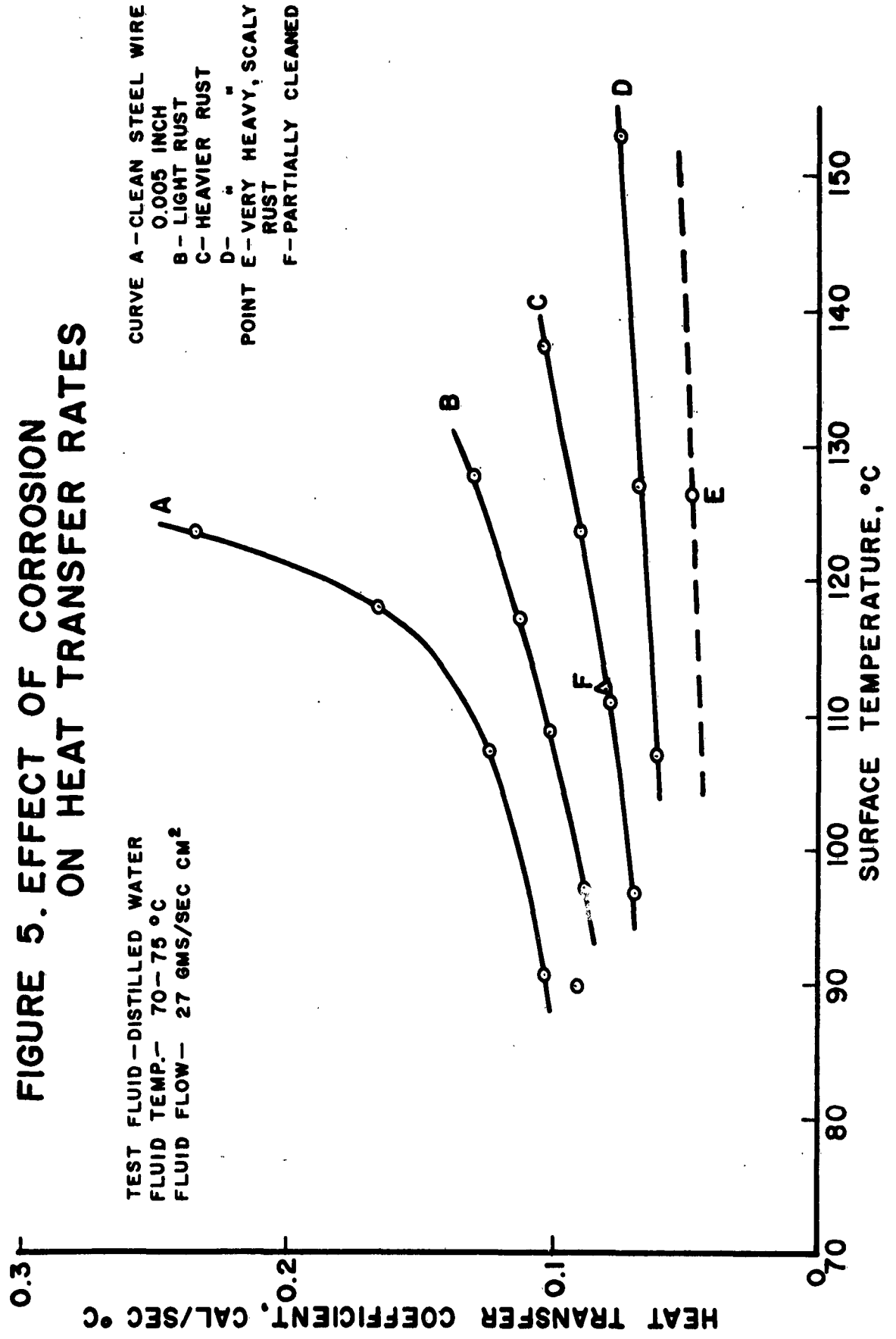
FIGURE 3. DIAGRAM OF ELECTRICAL CIRCUIT



- | | |
|---------------------------------|----------------------|
| A-0.06362 OHM STANDARD RESISTOR | G- RECTIFIER |
| B-9.91 " | H- POTENTIOMETER |
| C-75 OHM RESISTOR | I-12 VOLT BATTERY |
| D- SELECTOR SWITCH | J- AMMETER |
| E- 7.5 VOLT BATTERY | K- VARIABLE RESISTOR |
| F- TEST CELL | |



**FIGURE 5. EFFECT OF CORROSION
ON HEAT TRANSFER RATES**



**FIGURE 6. HEAT TRANSFER RATES
OF VARIOUS FLUIDS—COPPER**

CELL WIRE—0.004 INCH COPPER
FLUID TEMP.—70-75 °C
FLUID FLOW—27 GMS/SEC CM²

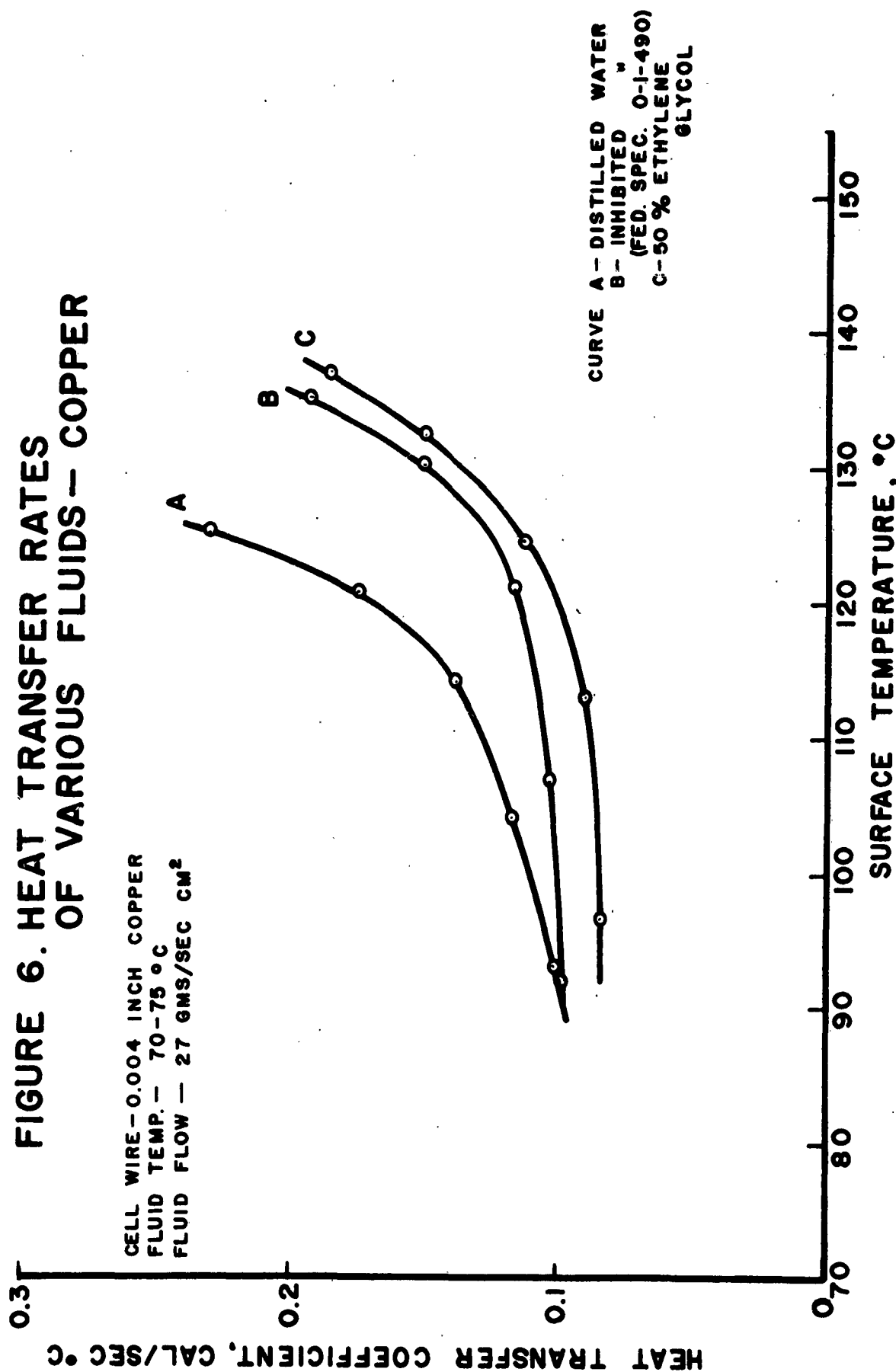
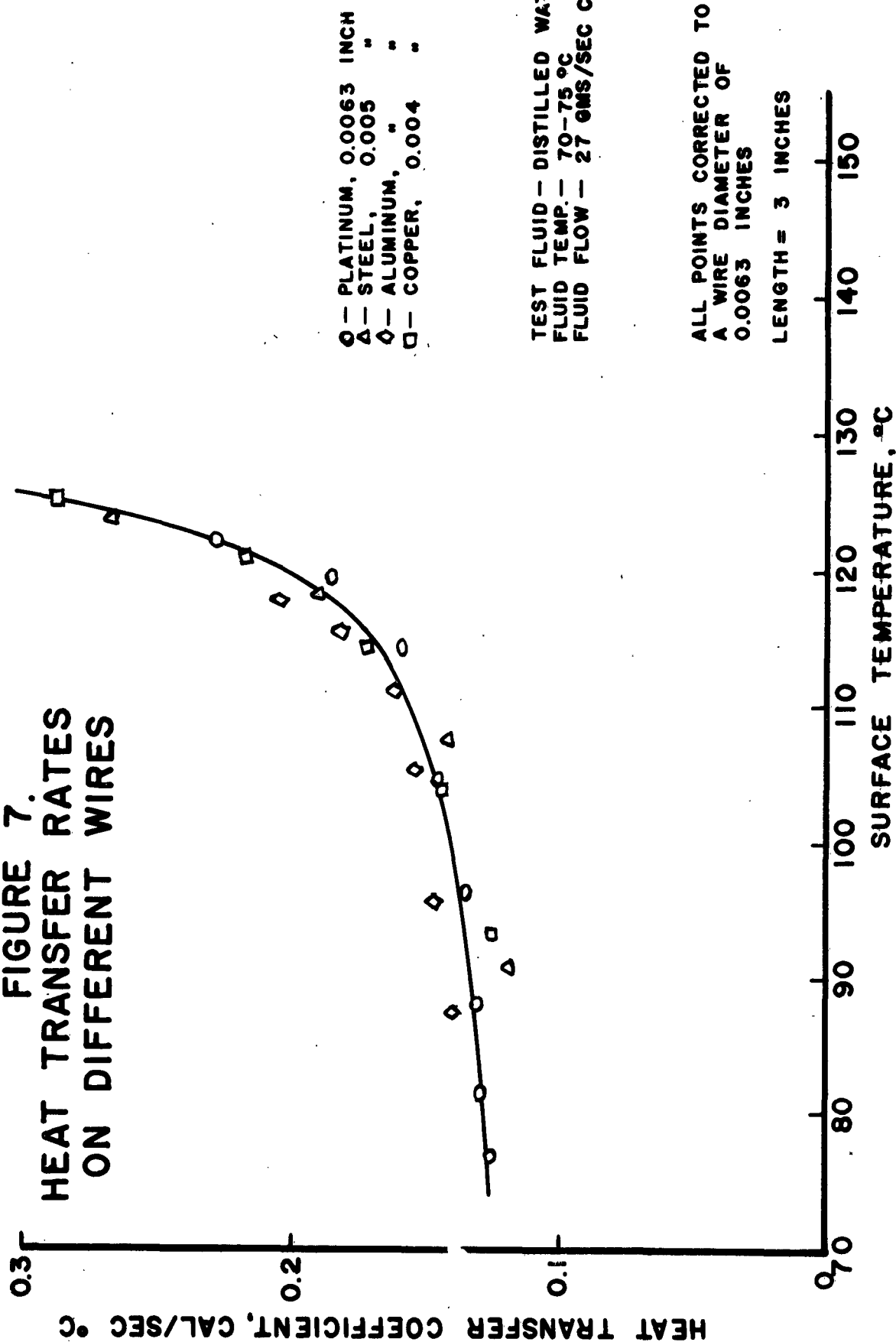


FIGURE 7.
HEAT TRANSFER RATES
ON DIFFERENT WIRES



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